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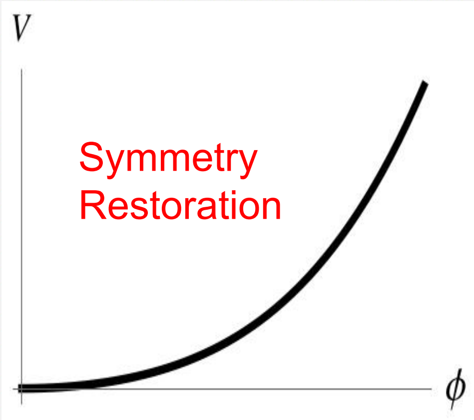
Detecting Electroweak Phase Transition and Implications

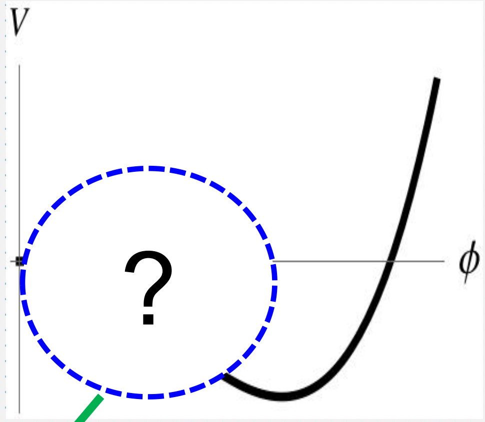
Huaike Guo

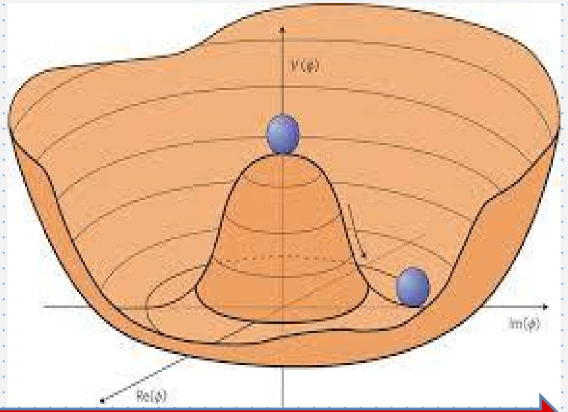
June 17, 2025

Shuo Guan, HG, Dian Jiao, Qingyuan Liang, Lei Wu, Yang Zhang (to appear)

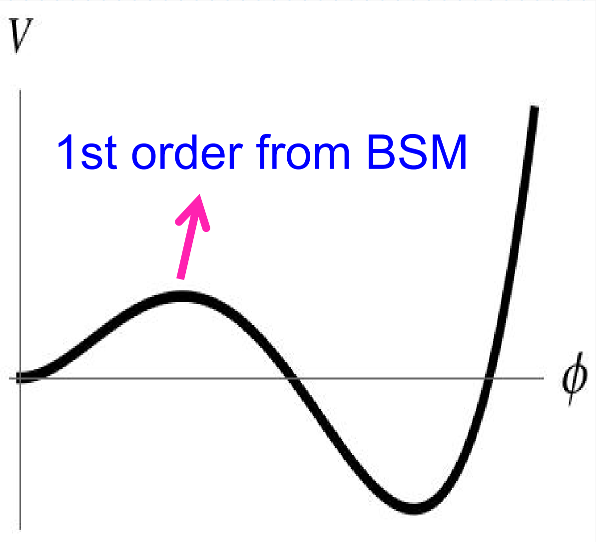
Electroweak Phase Transition

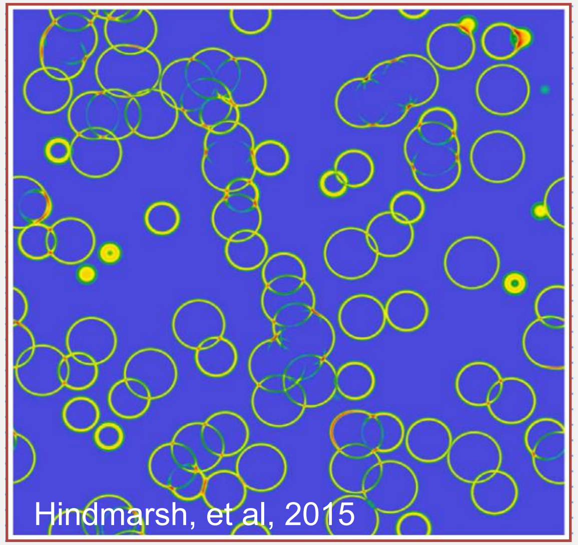






Temperature drops

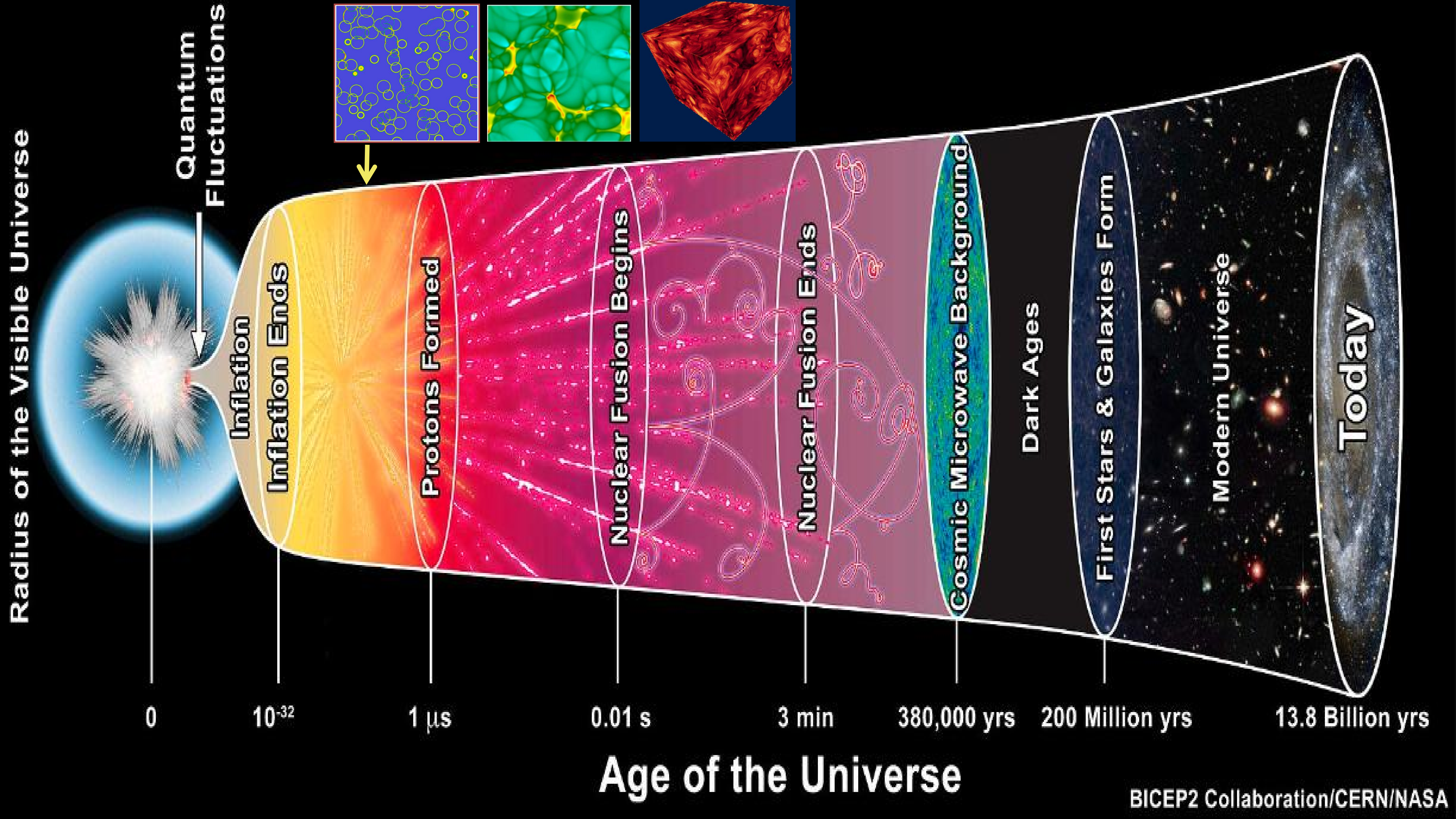




Electroweak Baryogenesis

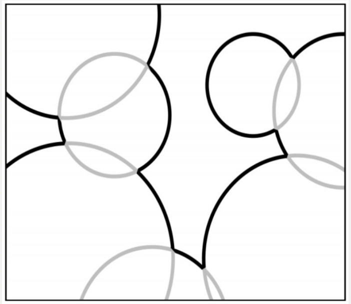
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- New particles, symmetries (LHC, GW)

Morrissey, Ramsey-Musolf, NJP[1206.2942]


Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

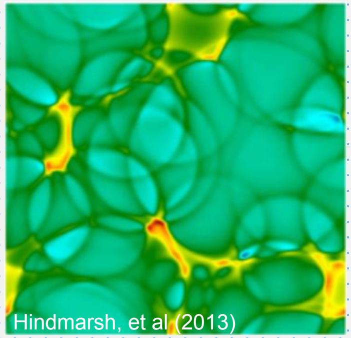
The Spectra

bubble collision



$$\Omega_{\rm coll}(f)h^2 = 1.67\times 10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3} S_{\rm env}(f),$$

sound waves



$$\Omega_{\rm sw}(f)h^2 = 2.65\times 10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2}$$ (RD)

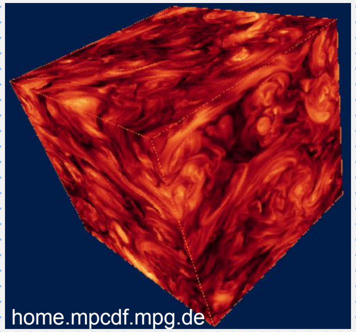
HG, Sinha, Vagie, White, JCAP [2007.08537]

$$\Upsilon = \frac{2[1-y^{3(w-1)/2}]}{3(1-w)}$$

HG, Yang Xiao, ... [2410.23666]

Reduces to Ellis, et al, JCAP [2003.07360]

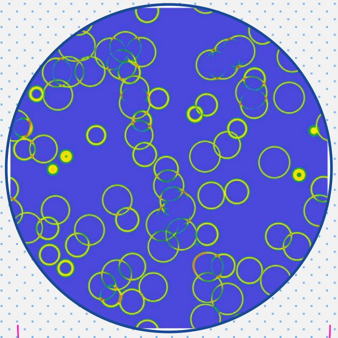
MHD



$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Chiara Caprini et al JCAP [1512.06239]

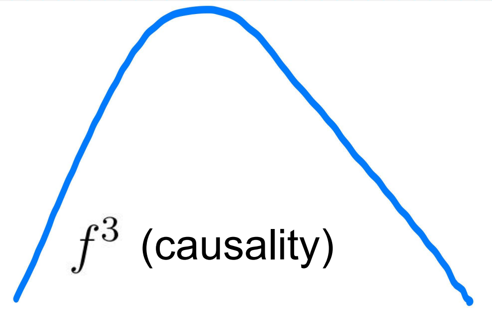
Basic Properties



Hubble size: 1/H*

$$f_{\rm now} = 1.65 \times 10^{-5} \left(\frac{f_{\rm PT}}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} {\rm Hz}$$

~100-1000



Cai, Pi, Sasak, PRD [1909.13728]

nHz (~100MeV) QCD scale

EPTA

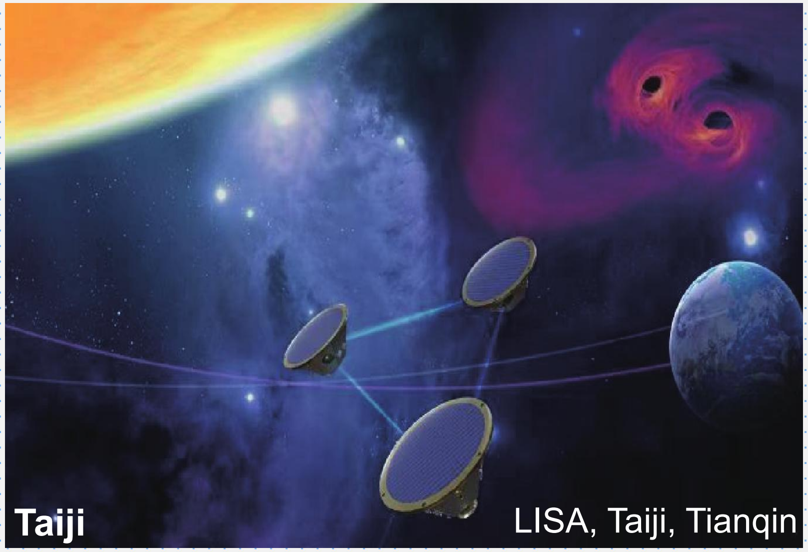
NANOGrav Physics Frontiers Center

PPTA

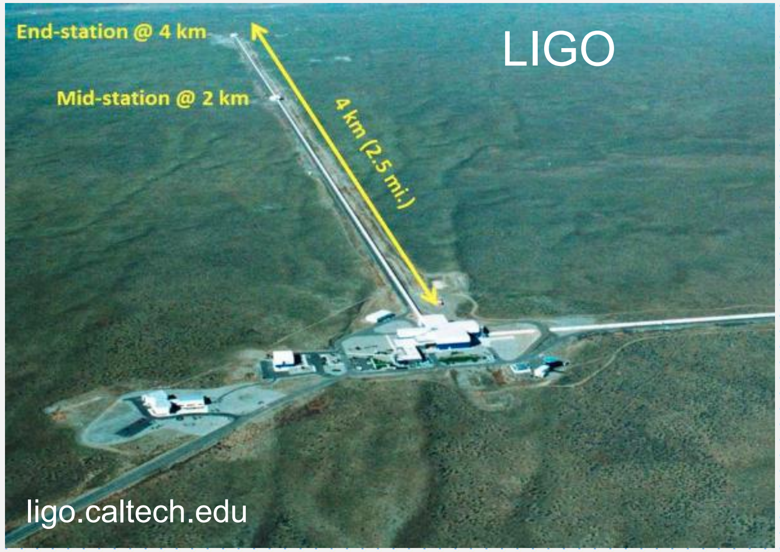
InPTA Indian Pulsar Timing Array

中国脉冲星测时阵列（CPTA）

~mHz : (~100GeV) weak scale



~100Hz (~PeV - EeV) high scale



Phenomenological Studies

Detection of early-universe gravitational-wave signatures and fundamental physics

Robert Caldwell, Yanou Cui, Huai-Ke Guo, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou, Kuver Sinha, Lian-Tao Wang, Graham White, Yue Zhao, Haipeng An, Ligong Bian, Chiara Caprini, Sebastien Clesse, James M. Cline, Giulia Cusin, Bartosz Fornal, Ryusuke Jinno, Benoit Laurent, Noam Levi, Kun-Feng Lyu, Mario Martinez, Andrew L. Miller, Diego Redigolo, Claudia Scarlata, Alexander Sevrin, Barmak Shams Es Haghi, Jing Shu, Xavier Siemens, Danièle A. Steer, Raman Sundrum, Carlos Tamarit, David J. Weir, Ke-Pan Xie, Feng-Wei Yang & Siyi Zhou — Show fewer authors

General Relativity and Gravitation **54**, Article number: 156 (2022) | Cite this article

arXiv > hep-ph > arXiv:2203.08206

High Energy Physics - Phenomenology

[Submitted on 15 Mar 2022]

Probing the Electroweak Phase Transition with Exotic Higgs Decays

Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Jessie Shelton, Yikun Wang, Ke-Pan Xie

arXiv > hep-ph > arXiv:2203.10046

High Energy Physics - Phenomenology

[Submitted on 18 Mar 2022]

Scalar-mediated dark matter model at colliders and gravitational wave detectors -- A White paper for Snowmass 2021

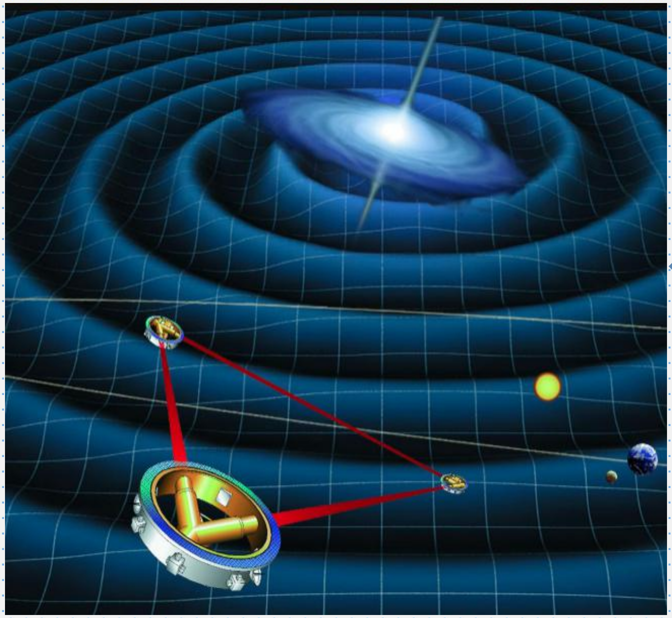
Jia Liu, Xiao-Ping Wang, Ke-Pan Xie

Snowmass 2021 White papers

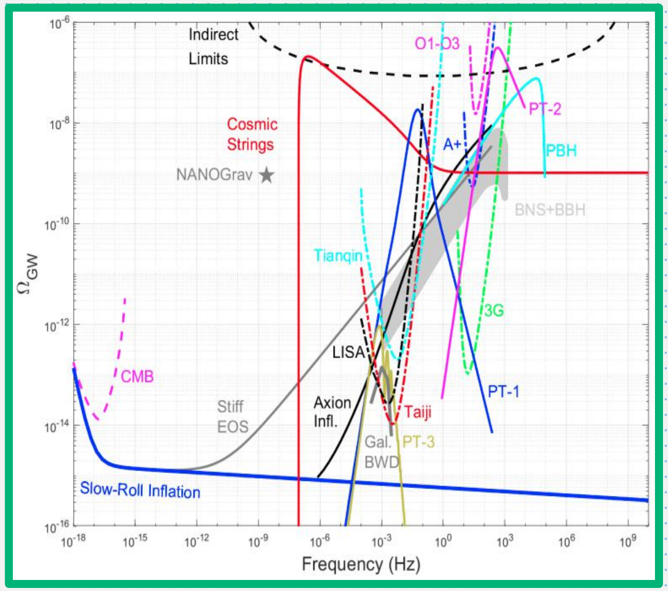
Models	Strong 1^{st} order phase transition	GW signal	Cold DM	Dark Radiation and small scale structure
SM charged				
Triplet [20–22]	✓	✓	✓	✗
complex and real Triplet [23] (Georgi-Machacek model)	✓	✓	✓	✗
Multiplet [24]	✓	✓	✓	
2HDM [25–30]	✓	✓		✗
MLRSM [31]	✓	✓	✗	✗
NMSSM [32–36]	✓	✓	✓	✗
SM uncharged				
S_r (xSM) [37–49]	✓	✓	✗	✗
2 S_r's [50]	✓	✓	✓	✗
S_c (cxSM) [49, 51–54]	✓	✓	✓	✗
$\mathrm{U(1)_D}$ (no interaction with SM) [55]	✓	✓	✓	✗
$\mathrm{U(1)_D}$ (Higgs Portal) [56]	✓	✓	✓	
$\mathrm{U(1)_D}$ (Kinetic Mixing) [57]	✓	✓	✓	
Composite SU(7)/SU(6) [58]	✓	✓	✓	
$\mathrm{U(1)_L}$ [59]	✓	✓	✓	✗
$\mathrm{SU(2)_D} \to$ global $SO(3)$ by a doublet [60–62]			✓	✗
$\mathrm{SU(2)_D} \to \mathrm{U(1)_D}$ by a triplet [63–65]			✓	✓
$\mathrm{SU(2)_D} \to Z_2$ by two triplets [66]			✓	✗
$\mathrm{SU(2)_D} \to Z_3$ by a quadruplet [67, 68]			✓	✗
$\mathrm{SU(2)_D} \times \mathrm{U(1)_{B-L}} \to Z_2 \times Z_2$ by a quintuplet and a S_c [69]			✓	✗
$\mathrm{SU(2)_D}$ with two dark Higgs doublets [70]	✓	✓	✗	✗
$\mathrm{SU(3)_D} \to Z_2 \times Z_2$ by two triplets [62, 71]			✓	✗
$\mathrm{SU(3)_D}$ (dark QCD) (Higgs Portal) [72, 73]	✓	✓	✓	
$G_{\mathrm{SM}} \times G_{\mathrm{D,SM}} \times Z_2$ [74]	✓	✓	✓	
$G_{\mathrm{SM}} \times G_{\mathrm{D,SM}} \times G_{\mathrm{D,SM}} \cdots$ [75]	✓	✓	✓	
Current work				
$\mathrm{SU(2)_D} \to \mathrm{U(1)_D}$ (see the text)	✓	✓	✓	✓

Ghosh, HG, Han, Liu, JHEP [2012.09758]

From Theory to Experiment



LIGO, LISA/Taiji/Tianqin, PTA, ...



Gravitational Wave Spectrum

α

β

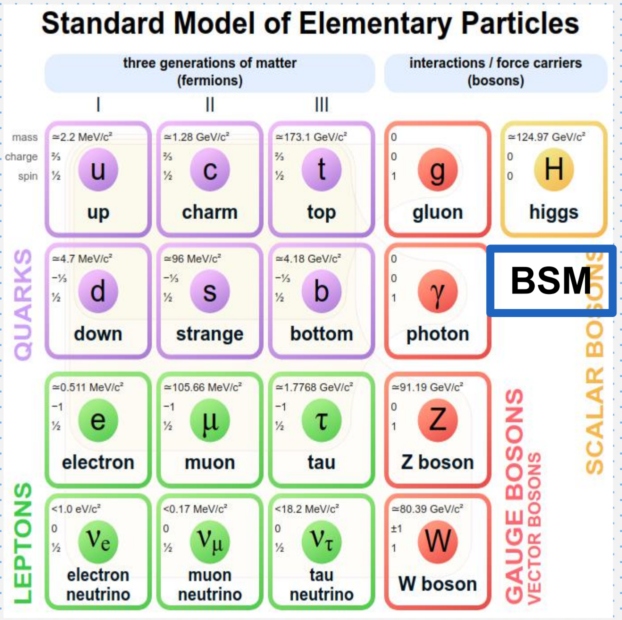
v_w

T_*

g_s

...

Phase Transition Parameters



Particle Physics Model

this way

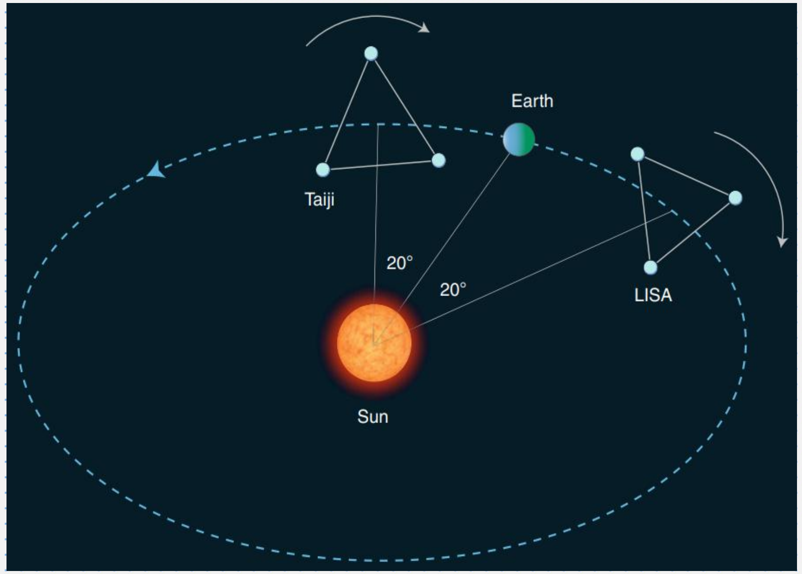
Questions to Answer

- Set limits when signal is absent
- Parameter estimation when signal is discovered
  - What is the precise shape of the signal spectrum?
  - What are the values of alpha, beta, vw, T*, etc?
  - What is the underlying particle physics model?
    - What are the values of the model parameters?
    - Can we infer properties of Higgs?
    - What does this imply for collider experiments?
  - ...

Detection in Space

Stochastic GW detection in space:

- With a single detector (this work)
- With a detector network (standard cross correlation method, LIGO)



Ruan, Liu, Guo, Wu, Cai, Nature Astron [2002.03603]

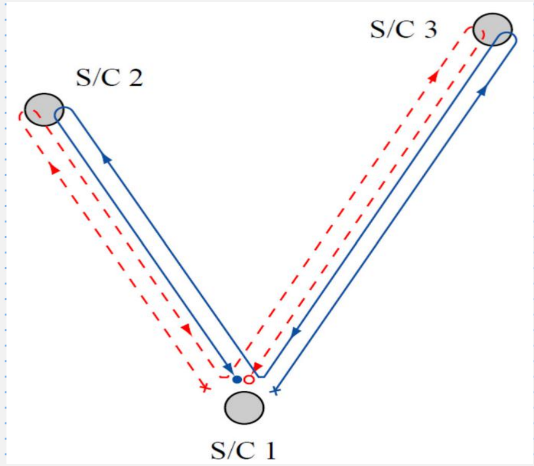
Studies on PT detection in space:

Gowling, Hindmarsh, Hooper, Torrado, JCAP [2209.13551]
Gowling, Hindmarsh, JCAP [2106.05984]
Boileau, et al, JCAP [2209.13277]
Lewicki, et al, PRD [2403.03769]
Caprini, et al, JCAP [2403.03723]

Cosmo SGB detectable down to $\Omega_{GW} \sim O(10^{-13})$

Boileau et al, MNRAS [2105.04283]

Detector Response

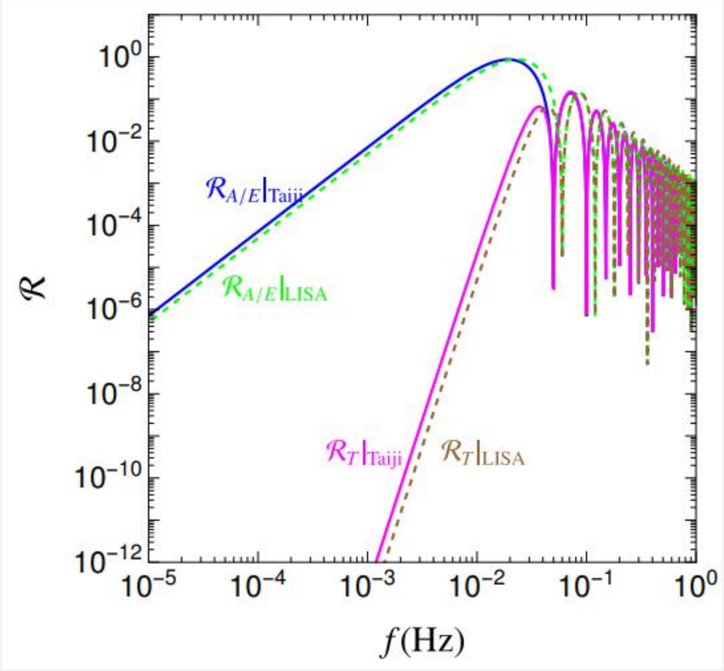


3 streams of data (orthogonal TDI channels)

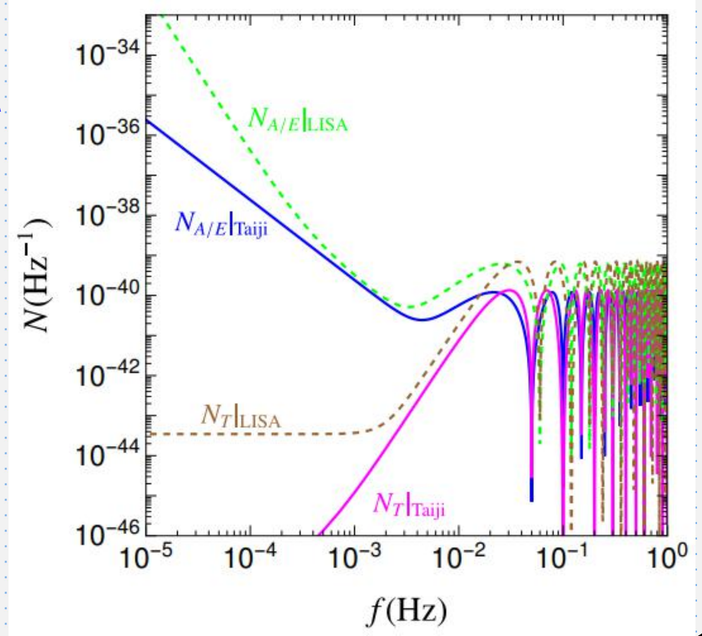
TDI: time-delay interferometry
Tinto, Dhurandhar, LRR, 2021

$$\langle \tilde{d}_a(f)\tilde{d}_b^{\star}(f')\rangle = \frac{1}{2}P_a(f)\delta_{ab}\delta(f-f')$$

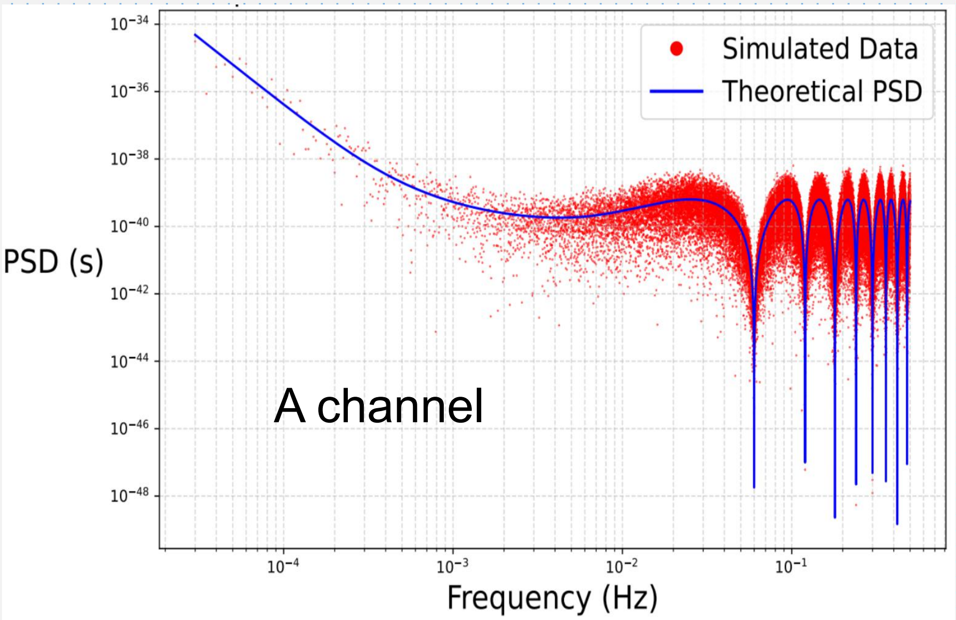
$$P_a(f) = \frac{3H_0^2}{4\pi^2}\frac{\Omega_{\rm GW}}{f^3}R_a(f) + N_a(f)$$



Idealized scenario:
2 noise parameters: Nacc, δx



Likelihood



The core of the statistical analysis: likelihood

both signal and noise behave as random variables

Bayesian framework

$$\mathcal{L} = \prod_{\kappa=1}^{N_0} \prod_{k=1}^{N/2} \frac{1}{8\pi^3 \sigma_A^2 \sigma_E^2 \sigma_T^2} \exp\left[- \sum_{a=A,E,T} \frac{\left| \tilde{d}_a^{\kappa}(f_k) \right|^2}{2\sigma_a^2} \right]$$

$$\sigma_a^2 = \frac{T f_s^2}{4} \left[\frac{3H_0^2}{4\pi^2} \frac{\Omega_{\rm GW}}{f^3} R_a(f) + N_a(f) \right]$$

$N_0 = 126$: number of segments

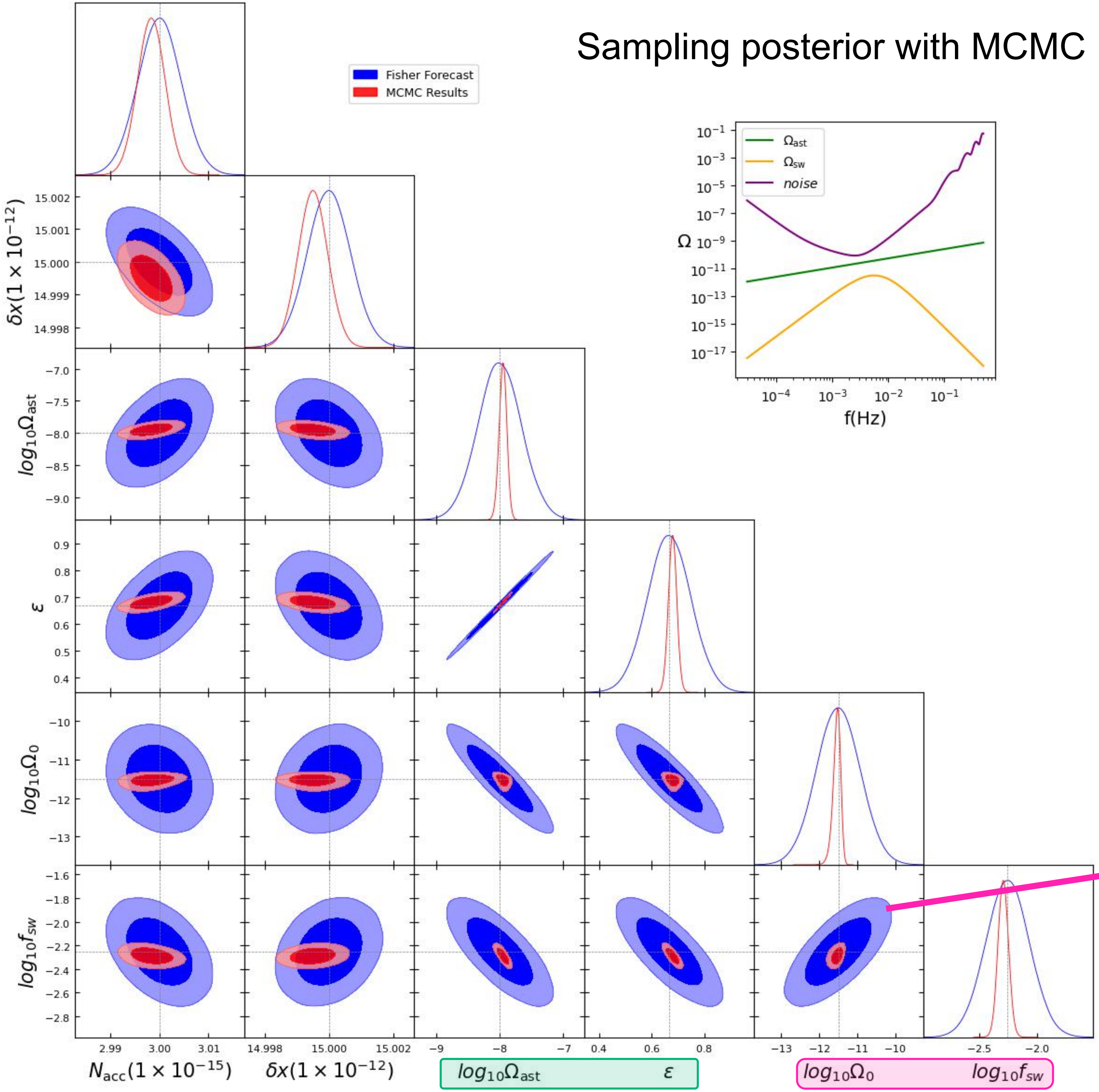
$N = 10^6$: frequency bins in one segment

$T = 1.26 \times 10^8\,\mathrm{s}$: observation time

$f_s = 1\,\mathrm{Hz}$: sampling frequency

astrophysical background
cosmological background (PT, etc)

Sampling posterior with MCMC

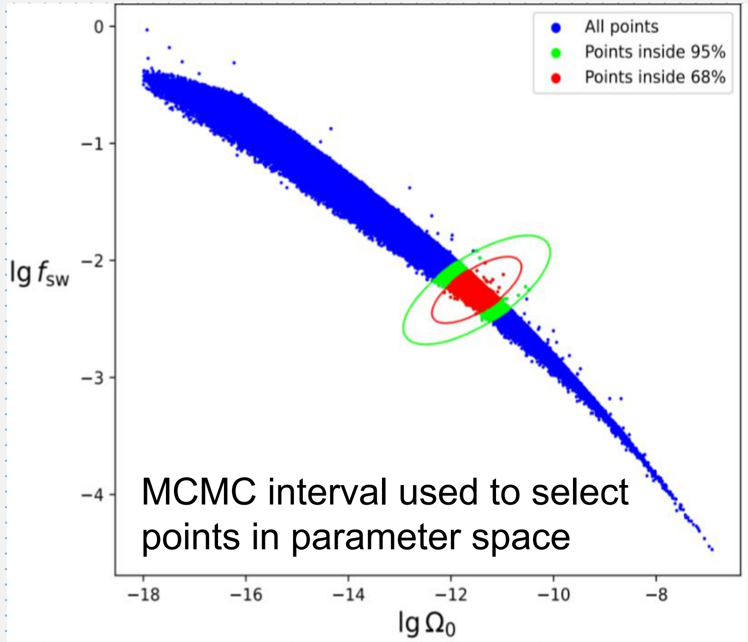


Simplified SW spectrum with no parameter degeneracy

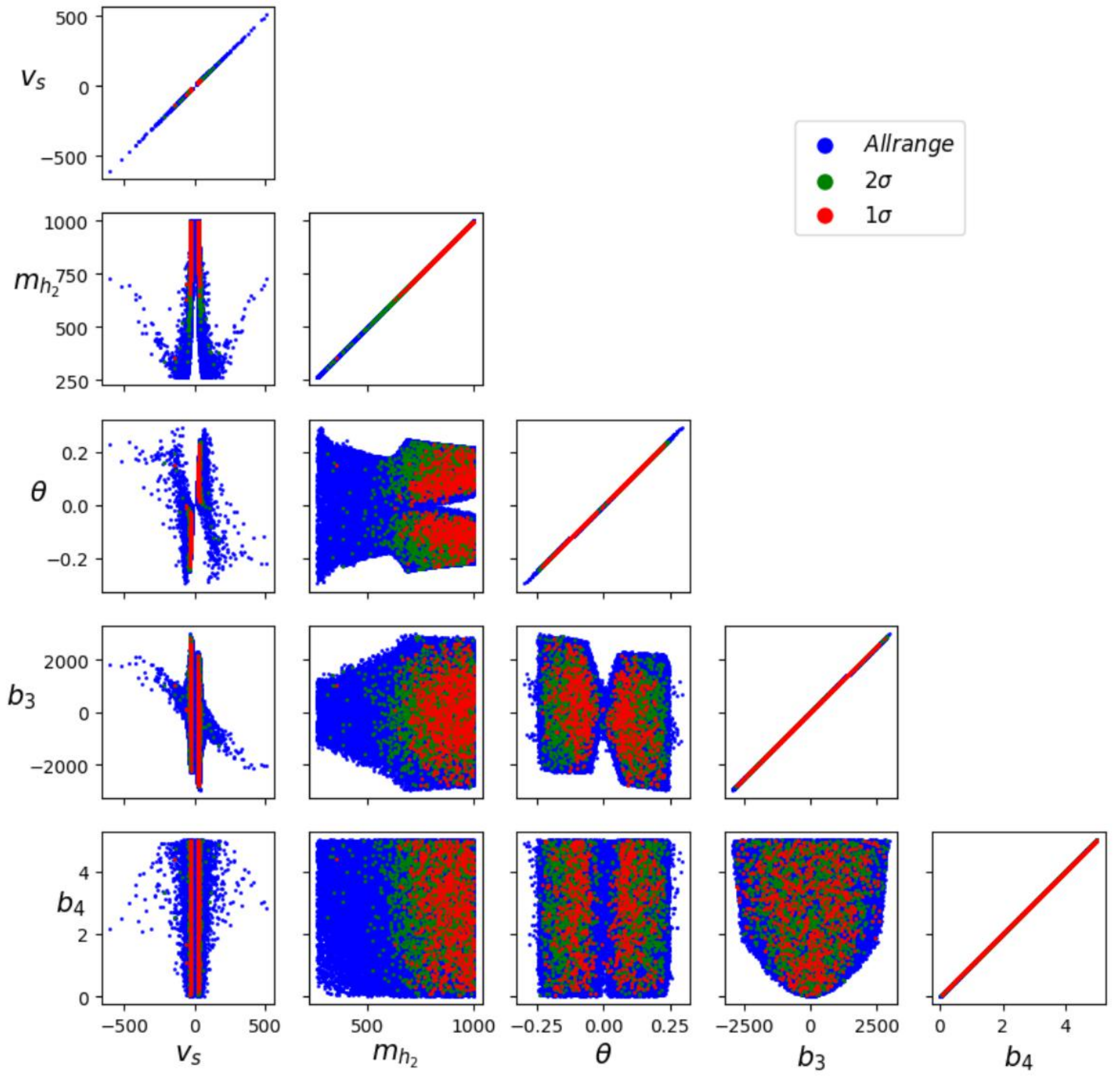
$$\Omega_{\rm sw}(f) = \Omega_0 \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{7/2}$$

$$\Omega_{\rm astro}(f) = \Omega_{\rm ast} \left(\frac{f}{f_{\rm ref}}\right)^{\varepsilon}$$

points from scan of xSM,
evading physical constraints



xSM Model



Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy, PRD [0706.4311]

$$V(\phi, S) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

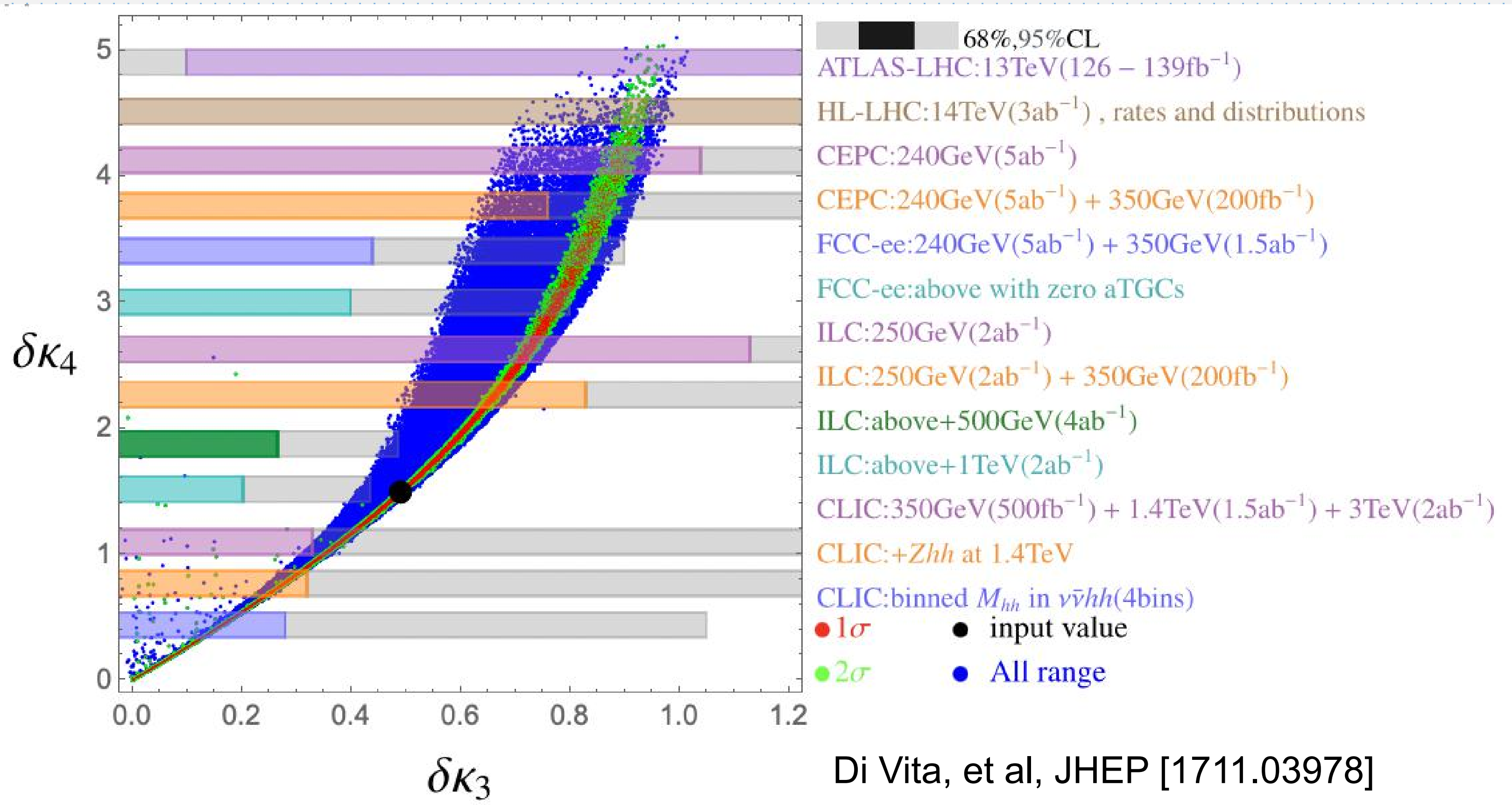
$$v_s, \quad m_{h_2}, \quad \theta, \quad b_3, \quad b_4$$

Points survive pheno constraints.

Alves, Ghosh, HG, Sinha, Vagie, JHEP [1812.09333]

Higgs Self-Couplings

$$\Delta\mathcal{L} = -\frac{1}{2}\frac{m_{h_1}^2}{v}(1+\delta\kappa_3)h_1^3 - \frac{1}{8}\frac{m_{h_1}^2}{v^2}(1+\delta\kappa_4)h_1^4.$$



Di Vita, et al, JHEP [1711.03978]

All scan points (blue) from Alves, Ghosh, HG, Sinha, Vagie, JHEP[1812.09333]

Caveat: theoretical uncertainties neglected, idealized detector configuration

Summary

- Simulation based study conducted for detection of GW from EWPT
- Bayesian parameter estimation performed with MCMC sampling
- Higgs self-couplings measurement done, though under idealized conditions

Thanks!